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An Improved Treatment of AC Space Charge Fields in Large Signal Simulation Codes

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An accurate representation of the AC space charge electric field is required in order to be able to predict the performance of linear beam tubes, including TWT's and klystrons, using a steady state simulation code like CHRISTINE [1]. The model implemented in the current release version of CHRISTINE is based on the assumption that the space charge reduction factor R is insensitive to axial wavenumber k , for a small range of k near $k_b \equiv \omega / v_b$, where ω is the circular frequency of the wave and v_b is the beam velocity. This assumption is usually a good one, but we have found cases in which the variation of R with k must be taken into account. We show how this can be done, and illustrate the effect in an example.

A useful expression for the space charge electric field in terms of the AC space charge density may be obtained by solving Maxwell's equations, subject to boundary conditions in a simplified structure, which is usually taken to be a cylindrical tube with the beam located along the axis (the beam could be an annular beam). The result is [2] that the space charge electric field in k -space may be written as a simple product of the so-called bunching factor (essentially the AC current density) and the space charge reduction factor, which depends on the radius of the cylinder, the frequency ω , and the axial wave-number k . The dependence of both functions is illustrated in Figure 1 in a sample case. The bunching factor is seen to depend strongly on k , with a large peak located at $k^+ \equiv k_b + k_{sc}$, corresponding to the slow space charge wave, and a much smaller peak located at $k^- \equiv k_b - k_{sc}$, corresponding to the fast space charge wave, where k_{sc} is the plasma wave-number, proportional to the square root of the beam current. The space charge reduction factor, R is seen to be smoothly varying, though not constant, in the range $k^- \leq k \leq k^+$. The algorithm in previous release versions

of CHRISTINE sets R equal to its value at

$$k = \frac{k^+ + k^-}{2} = k_b.$$

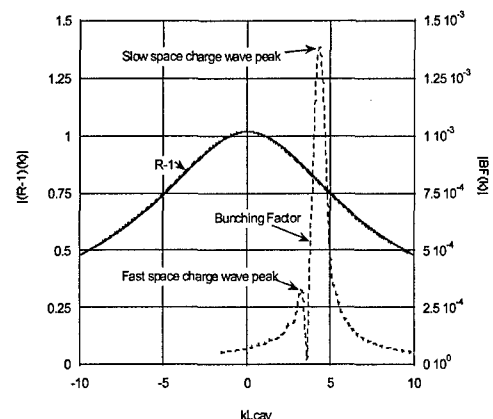


Figure 1: Space charge reduction factor R and bunching factor (AC current) as functions of axial wavenumber k , for a C-band CC-TWT.

In some cases it turns out that this approximation does not produce a sufficiently accurate description of the space charge electric field, and consequently the variation of the space charge reduction factor with k must be taken into account.

This may be done exactly by direct Fourier inversion of the product of R and the bunching factor from k -space to coordinate (z)-space; the result is a convolution integral, which can be time consuming to evaluate. An alternate, though approximate, method is to expand $R(k)$ in k -space around $k = k_b$, and keep only the first two terms,

$$R(k) \approx R(k_b) + (k - k_b)R'(k_b) \quad (1)$$

Inverting now from k -space to z -space produces the original expression used in CHRISTINE plus a correction proportional to the z -derivative of the AC space charge density.

The physical meaning of the correction is that it takes into account the local, slow axial variation of the bunching, due to the growth (gain) and phase shift of the slow wave. An estimate of the size of the correction relative to the leading term is given in small signal theory by

$$\left| \Delta k \frac{R'(k_b)}{R(k_b)} \right| \quad (2)$$

where $\Delta k \equiv \Delta k_r + i\Delta k_i$ is the complex shift of the wavenumber, due to the interaction of the slow wave with the beam. Δk_r determines the phase shift and Δk_i is the spatial growth rate of the wave. The magnitude of the correction depends therefore on the circuit properties, beam current, voltage, and radius, and the frequency of the signal. In high gain tubes, especially in some mm-wave amplifiers, this correction could become very important.

Results for the computation of small signal gain versus frequency using three different methods for computing the AC space charge field for a C-band coupled cavity TWT are shown in Figure 2. The three methods use (i) the first term (only) of Eq. (1) [This is the original method used in CHRISTINE.], (ii) both terms of Eq. (1), and (iii) the full convolution integral. We see that in this C-band case, as in other cases that we have studied, the use of the linear approximation (ii) for $R(k)$ gives results in very close agreement with those obtained using the exact convolution integral (iii), both being slightly different from those obtained using (i). In other cases we have tried, all three methods give excellent agreement in both small and large signal tests. All three methods used roughly -- within 20%

or so -- the same amount of CPU time for the cases shown in Figure 2.

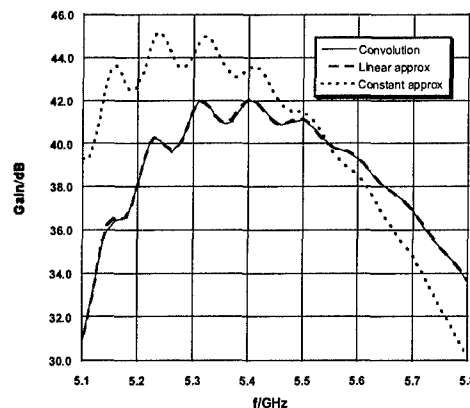


Figure 2: Computed small signal gain vs. frequency for a C-band CC-TWT using three different methods for computing the AC space charge electric field.

A future release of the CHRISTINE code will include an option to use any of the three methods (i), (ii), or (iii) for the computation of the AC space charge field.

References

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2. S.M. Miller, et.al., "Theory of relativistic backward wave oscillators operating near cutoff," *Phys. Plasmas* 1 730-740 (1994). Eq. (B-8).

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